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Effects of Resin Thickness on the Stress Intensity Factors of Edge-cracked Adhesive Joints

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***Abstract*—The effects the thickness of epoxy resin on the stress intensity factors (SIFs) of the edge-cracked adhesive joints subjected to external loads are investigated in the current paper. The three-layered joints composed of Silicon, epoxy resin and FR-4.5 are widely seen in the package solutions of CSP/FBGA for electronic devices. Cracks or delaminations from resin-substrate interface or resin-silicon interface are the common failure modes in plastic IC packages. However, it is difficult to determine the exact stress state of a bi-material interface due to the oscillatory singularity. In this paper, the SIFs of the single edge-cracked joints are determined accurately by using the Crack Tip Stress Method. Then, the effects of resin thickness on the SIFs of various edge interface cracks under uniform tension are investigated by varying the resin thickness and crack length. It was found that the SIFs grow with the increment of resin thickness and reach constants when the resin thickness is larger than the width of the joint.**

Keywords—Stress intensity factors; Stress singularity; Adhesive joints; Edge interface crack

I. INTRODUCTION

Fatigue cracks are normally observed around the vicinity in adhesive joints and areas of discontinuities due to the high stress concentration, residual stresses and bonding defects. The presence of a crack affects the performance of a structure, and the propagation may eventually cause a through thickness crack which results in the failure of a structure. In linear elastic fracture mechanics, the stress intensity factor (SIF) is used to predict the stress state of a crack subjected to remote load. Therefore, quite a lot research has been devoted to the analysis of the SIFs of the crack problems.

Nisitani [1] proposed a simple method "Crack Tip Stress Method" for determining SIFs for crack problems by using FE Method. Then, Oda et al [2] extended this method to analyze the interface crack problems by making the singular terms the same for the reference and target unknown problems. In the previous studies [3-5], we solved the SIFs of several edge interface cracks in bi-material bonded strips for arbitrary material combinations. These pioneering work provide a convenient manner to obtain the SIFs of the interface crack problems.

Adhesively bonded joints are widely observed in the package solutions of CSP/FBGA for electronic devices. In the CSP/FBGA package, silicon chip is bonded to the FR-4.5 substrate by using epoxy resin. Delaminations from resin-substrate/resin-silicon interface are the common failure modes in plastic IC packages. Normally, an edge interface crack leads higher risk of structure failure than a central crack. Therefore, the stress intensity factors of the edge-cracked adhesively joints subjected to uniform tension are computed in this research. By varying the thickness of epoxy resin (interlayer) and crack length, the effects of resin thickness on SIFs of the edge interface cracks in adhesive joints subjected to uniform tension are systematically investigated.

II. EASE OF USE

A. Formulation for the Interface crack problems

Oda et.al. [2], extended the crack tip stress method to the interface crack problems by creating the same singular stress fields for the reference and target unknown problems. A definition of the SIFs for an interface crack in bonded dissimilar materials was proposed by Erdogan [6]. The stress distributions along the interface are defined as shown in (1).

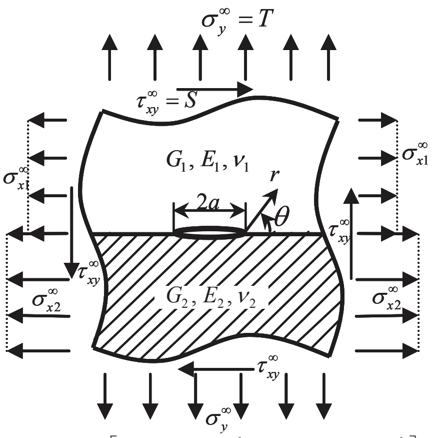
$$\sigma_y + i\tau_{xy} = \frac{K_I + iK_{II}}{\sqrt{2\pi r}}\left(\frac{r}{2a}\right)^{i\varepsilon}, r \to 0 \tag{1}$$

Here, σ_y, τ_{xy} denote the stress components near the crack tip, r is the radial distance from the crack tip, and ε is the bi-elastic constant given by:

$$\varepsilon = \frac{1}{2\pi} ln\left[\left(\frac{\kappa_1}{G_1} + \frac{1}{G_2}\right) / \left(\frac{\kappa_2}{G_2} + \frac{1}{G_1}\right)\right] \tag{2}$$

$$\kappa_m = \begin{cases} 3-4\nu_m \ (plane \quad strain) \\ 3-\nu_m / 1+\nu_m \ (plane \quad stress) \end{cases}, \quad (m=1,2) \tag{3}$$

where $G_m\ (m=1,2)$ and $\nu_m\ (m=1,2)$ are the shear moduli and poisson's ratios of either respective materials. The real and imaginary parts of the oscillatory SIFs $K_I + iK_{II}$ in (1) may be separated as:



$$\sigma_{x2}^\infty = \frac{1}{1+\kappa_2}\left[\frac{G_2}{G_1}(1+\kappa_1)\sigma_{x1}^\infty + \left\{3-\kappa_2 - \frac{G_2}{G_1}(3-\kappa_1)\sigma_y^\infty\right\}\right]$$

Fig. 1. Demonstration of the reference problem

$$K_I = \lim_{r\to 0}\sqrt{2\pi r}\,\sigma_y\left(\cos Q + \frac{\tau_{xy}}{\sigma_y}\sin Q\right) \tag{4}$$

$$K_{II} = \lim_{r\to 0}\sqrt{2\pi r}\,\tau_{xy}\left(\cos Q - \frac{\sigma_y}{\tau_{xy}}\sin Q\right) \tag{5}$$

$$Q = \varepsilon \ln\left(\frac{r}{2a}\right) \tag{6}$$

let's consider two different interface crack problems A and B with the same crack lengths $a = a_0$ and the same combination of materials $\varepsilon = \varepsilon_0$, assuming the SIFs of problem A are given in advance and those for problem B are yet to be solved. Problem A is termed the reference whose values are marked with *, and problem B is termed the target unknown problem. Examining the points with the same radial distances $r = r_0$ for the two problems A and B, then gives $\left[Q^*\right]_A = \left[Q\right]_B = \varepsilon_0 \ln\left(\frac{r_0}{2a_0}\right)$. Recall (4) and (5), a proportional relationship given in (7) is established if and only if (8) can be satisfied,

$$\frac{\left[K_I\right]_B}{\left[K_I^*\right]_A} = \frac{\left[\sigma_y\right]_B}{\left[\sigma_y^*\right]_A}, \frac{\left[K_{II}\right]_B}{\left[K_{II}^*\right]_A} = \frac{\left[\tau_{xy}\right]_B}{\left[\tau_{xy}^*\right]_A} \tag{7}$$

$$\left[\frac{\tau_{xy}^*}{\sigma_y^*}\right]_A = \left[\frac{\tau_{xy}}{\sigma_y}\right]_B \tag{8}$$

Then the SIFs of the given unknown problem (problem B) can be computed using (9) and (10). The condition of (8) can be satisfied by choosing a suitable external load as discussed in the following section.

$$\left[K_I\right]_B = \frac{\left[\sigma_y\right]_D\left[K_1^*\right]_A}{\left[\sigma_y^*\right]_A} = \frac{\left[\sigma_{y,FEM}\right]_B\left[K_1^*\right]_A}{\left[\sigma_{y,FEM}^*\right]_A} \tag{9}$$

$$\left[K_{II}\right]_B = \frac{\left[\tau_{xy}\right]_B\left[K_2^*\right]_A}{\left[\tau_{xy}^*\right]_A} = \frac{\left[\tau_{xy,FEM}\right]_B\left[K_2^*\right]_A}{\left[\tau_{xy,FEM}^*\right]_A} \tag{10}$$

B. The determination of the reference problem and its external load

In this research, a crack along the interface of two bonded dissimilar half-planes subjected to tension and shear as shown in Fig.1 is treated as the reference problem. The analytical solution of the SIFs for the reference problem takes the form:

$$K_I^* + iK_{II}^* = (\sigma_y^\infty + i\tau_{xy}^\infty)\sqrt{\pi a}(1+2i\varepsilon) \tag{11}$$

Let $\sigma_{y0,FEM}*, \tau_{xy0,FEM}*$, $\sigma_{y0,FEM}^{\sigma_y^\infty=1,\tau_{xy}^\infty=0}*, \tau_{xy0,FEM}^{\sigma_y^\infty=1,\tau_{xy}^\infty=0}*$ and $\sigma_{y0,FEM}^{\sigma_y^\infty=0,\tau_{xy}^\infty=1}*, \tau_{xy0,FEM}^{\sigma_y^\infty=0,\tau_{xy}^\infty=1}*$ denote the crack tip stress components of the reference under combined remote tension and shear $\sigma_y^\infty, \tau_{xy}^\infty$, pure unit tension $\sigma_y^\infty = 1, \tau_{xy}^\infty = 0$ and pure unit shear $\sigma_y^\infty = 0, \tau_{xy}^\infty = 1$, respectively. Using the principle of superposition, then $\sigma_{y0,FEM}*, \tau_{xy0,FEM}*$ can be expressed as:

$$\sigma_{y0,FEM}* = \sigma_{y0,FEM}^{\sigma_y^\infty=1,\tau_{xy}^\infty=0}* \times \sigma_y^\infty + \sigma_{y0,FEM}^{\sigma_y^\infty=0,\tau_{xy}^\infty=1}* \times \tau_{xy}^\infty \tag{12}$$

$$\tau_{xy0,FEM}* = \tau_{xy0,FEM}^{\sigma_y^\infty=1,\tau_{xy}^\infty=0}* \times \sigma_y^\infty + \tau_{xy0,FEM}^{\sigma_y^\infty=0,\tau_{xy}^\infty=1}* \times \tau_{xy}^\infty \tag{13}$$

Inserting (12) and (13) into (8) gives the solution of $\tau_{xy}^\infty / \sigma_y^\infty$ needed for determining the external loads applied to the reference problem.

$$\frac{\tau_{xy}^\infty}{\sigma_y^\infty} = \frac{\sigma_{y0,FEM} \times \tau_{xy0,FEM}^{\sigma_y^\infty=1,\tau_{xy}^\infty=0}* - \tau_{xy0,FEM} \times \sigma_{y0,FEM}^{\sigma_y^\infty=1,\tau_{xy}^\infty=0}*}{\tau_{xy0,FEM} \times \sigma_{y0,FEM}^{\sigma_y^\infty=0,\tau_{xy}^\infty=1}* - \sigma_{y0,FEM} \times \tau_{xy0,FEM}^{\sigma_y^\infty=0,\tau_{xy}^\infty=1}*} \tag{14}$$

Let $\sigma_y^\infty = 1$ so that τ_{xy}^∞ can be determined. Inserting $\sigma_y^\infty = 1, \tau_{xy}^\infty$ into (11) gives the SIFs of the problem A. Finally, the SIFs of problem B can be yielded using (9) and (10).

III. Analytical Model and Specifications

The MSC.MARC 2013 finite element analysis package is used to compute the stress components in this research. Fig.2a shows the FE model geometric configurations for the reference problem. The crack length for the dissimilar bonded half-planes shown in Fig.2 is set to $a = 0.1mm$ in this research. It

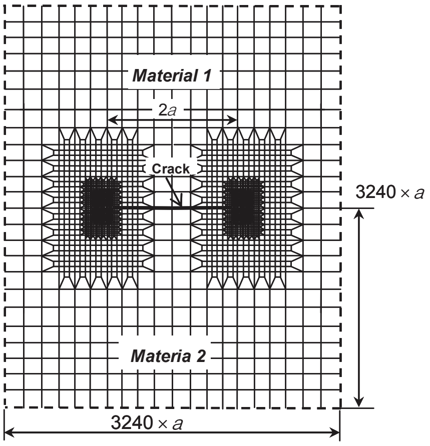


Fig. 2. FE model geometric configurations and mesh pattern for the reference problem

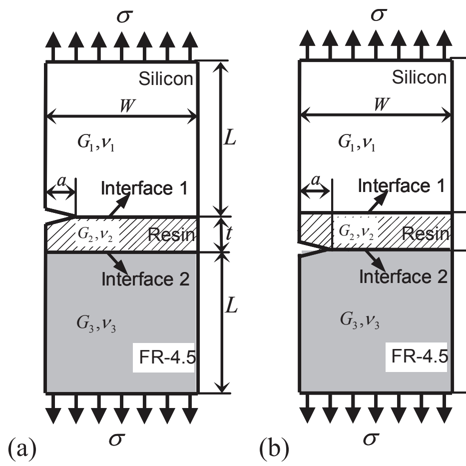


Fig. 3. Single-edge interface crack on (a) interface 1 and (b) interface 2 of an adhesively bonded strip

should be noted that the FE stress component values at the crack tip for the reference problem converge as the width of the model is larger than 1500 times the crack length a [2]. Then a plate width of $W = 1620 \times 2a = 324mm$ and a length of $L = 2W = 648mm$ are used to model the reference problem ($L = 2W, W/a = 1620$).

The geometric configurations of the analytical models for the target problem are demonstrated in Fig.3a and b, respectively. It is supposed that a same crack length of a has initiated at the interface 1 and 2 as shown in Fig.3(a) and (b). The singular regions around the crack tip of both the reference and the target problems are well refined in a self-similar manner. Fig2 also shows the FE mesh type in the vicinity of crack tip. The singular region is refined with increasing the number of mesh layers, and the element size for each inferior layer is one third of the superior one. The minimum element sizes are kept the same for the reference and target unknown problems. Furthermore, Eight-node quadrilateral elements in plane strain are used for both the reference and the target unknown problems.

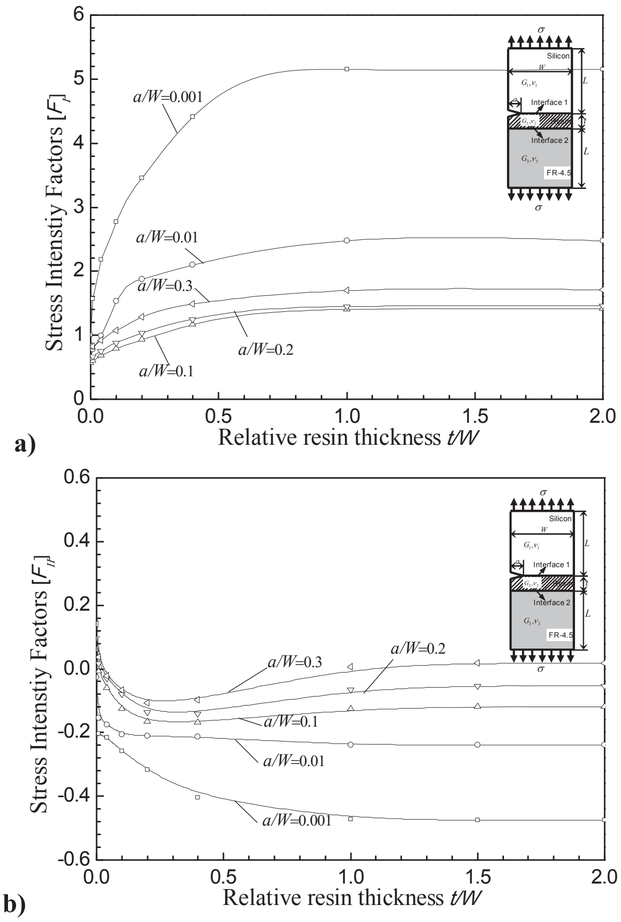


Fig. 4. Stress intensity factors (a) FI and (b) FII for interface 1

The three-layered bonded joints are composed of Silicon (IC chip), resin and FR-4.5(substrate) which are widely observed in the chip size packaging technology of electronic devices. The elastic parameters are tabulated in Table I [7].

TABLE I. PROPERTIES FOR ADHESIVELY BONDED JOINT (CSP IN THE ELECTRONIC DEVICE) [7]

Material Property	**Three-layered bonded joint**		
	Silicon	***Resin***	***FR-4.5***
Young's modulus (GPa)	166	2.74	15.34
Poisson's ratio	0.26	0.38	0.15

IV. RESULTS AND DISCUSSIONS

Two-dimensional plane-strain problems of the edge interface cracks initiated at interface 1 and 2 of the adhesive joints are computed for various crack lengths and resin thicknesses, and they are plotted in Fig.4 and 5, respectively. The relative crack length changes from 0.001 to 0.3 (*a/W*=0.001, 0.01, 0.1, 0.2, 0.3), and the relative thickness of epoxy resin *t/W* varies from 0.001 to 2 (*t/W*=0.001, 0.01, 0.04, 0.1,0.2,0.4,1,1.5,2). As can be seen from Fig.4. and Fig.5, normalized F_I reduces with the decrease of the thickness of epoxy resin for a fixed crack length. However, F_{II} does not

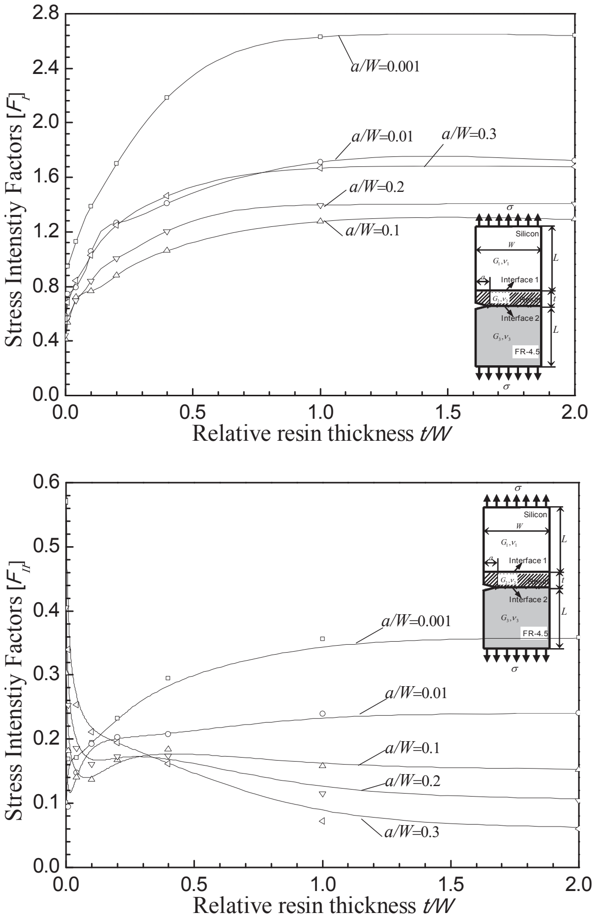


Fig. 5. Stress intensity factors (a) FI and (b) FII for interface 2

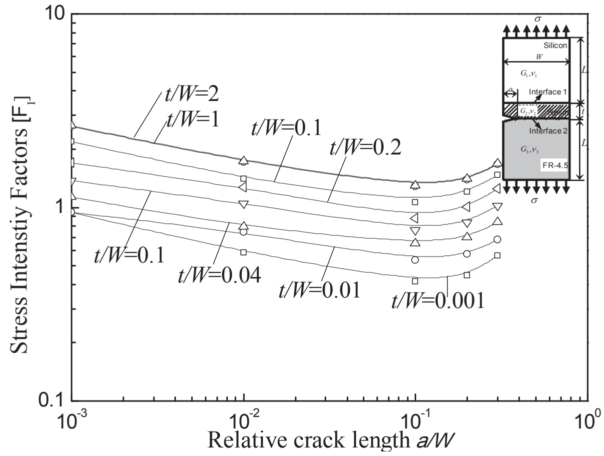


Fig. 6. Double logarithmic relationship between FI and relative crack length a/W for the edge crack at interface 2

behave a similar monotonic varying tendency. The values of F_{II} are almost one tenth of that of F_I for a given crack. And F_I plays a more important role than F_{II} in the failure analysis. However, for the case of extremely thin epoxy resin (*a/W*=0.001), the magnitudes of F_I and F_{II} are almost to the same level, especially for the edge crack on resin-FR4.5 interface. Tensile and shear modes are equally important in this case. For a given crack length and resin thickness, the SIFs of the edge interface crack at the Si-resin interface are greater than those of the crack at the resin-FR4.5 interface. Furthermore, Fig.4 and 5 also show that the SIF values reach to upper limit values asymptotically when the thickness of interlayer is bigger than the width of the strip (*t/W*>1). Actually, when *t/W*>1, the SIFs of the three-layered joints are in good agreement with those of the bi-material bonded strip without the material of the third layer in the joints.

Fig.6 depicts the double-logarithmic relationship between F_I and the relative crack length *a/W* for the edge interface crack at interface 2. Similar varying tendency can also be found from cracks at interface 1. In this graph, regarding a given thickness of epoxy resin, F_I decreases to a minimum value with the increment of the crack length for the extremely shallow crack case, and then rises with the continued growth of the crack length. This is due to the overlapped effect of the free-edge singularity and crack-tip singularity[4,5].

V. Conclusions

In this paper, the SIFs of the edge-cracked adhesive joint which is widely seen in CSP/FBGA package solutions, were systematically computed with varying various crack lengths and resin thicknesses. Conclusions are summarized as follows.

1. For a given fixed relative crack length, F_I grows with the increment of the thickness of epoxy resin. F_I and F_{II} reach to constants when the thickness of resin is larger than the width of the joint.

2. For a given thickness of epoxy resin, F_I decreases to a minimum value with the increment of crack length for the extremely shallow crack case, and then rises with the continued growth of the crack length.

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